SHINE Practicum Lectures Part 2

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Space Radiation Environments and NSRL Simulations

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SHINE Practicum

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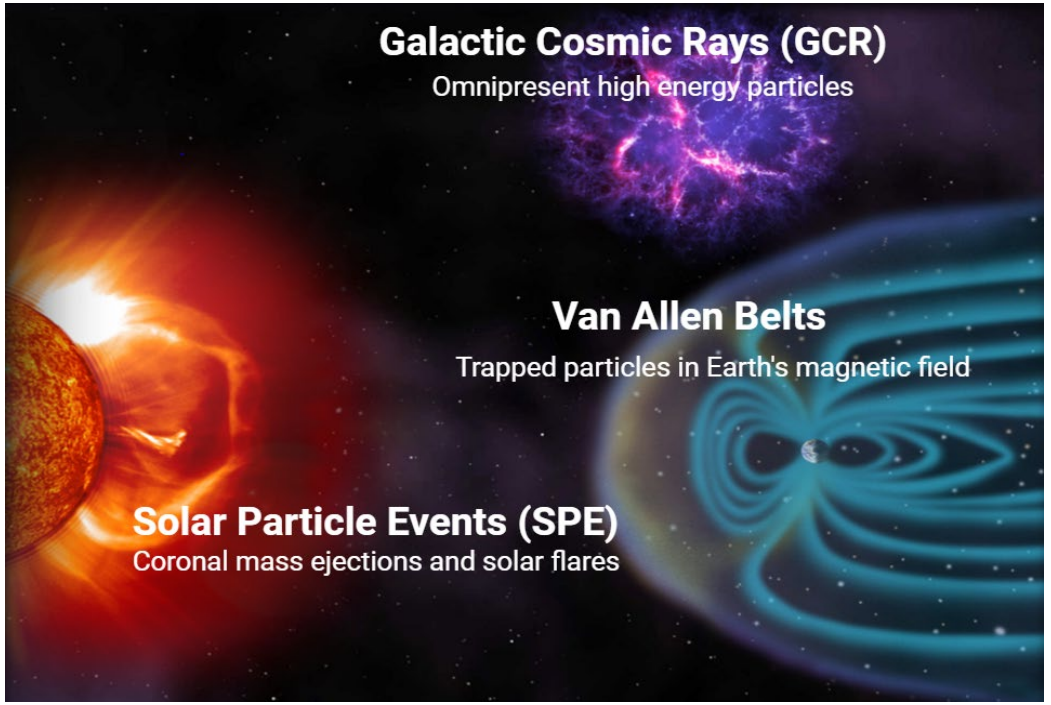
Background

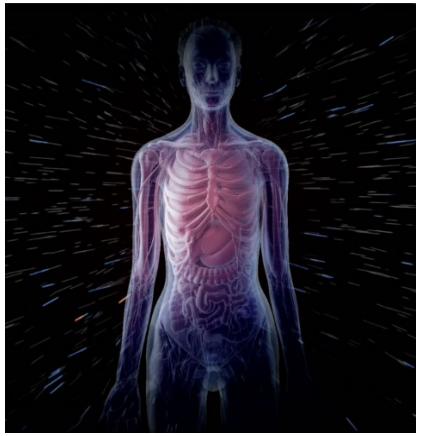
- Space radiation is identified by NASA as one of the five hazards of human spaceflight

https://www.nasa.gov/ochmo-hmta-human-spaceflight-hazards/

Background

- Space radiation-induced health risks include
  - Carcinogenesis
  - Cardiovascular disease
  - Damage to the central nervous system
- For long duration missions beyond low Earth orbit (LEO) risks mainly arise from galactic cosmic rays (**GCR**) and solar particle events (**SPE**)
- Characterization and effective mitigation of these risks relies on ground-based experiments
  - Accurate simulation of space radiation environment at NSRL

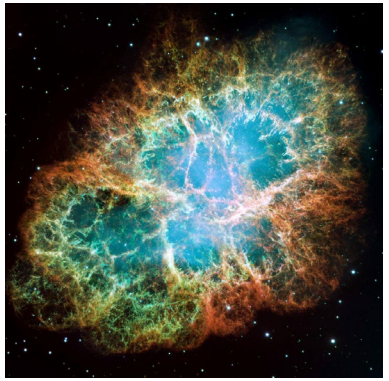




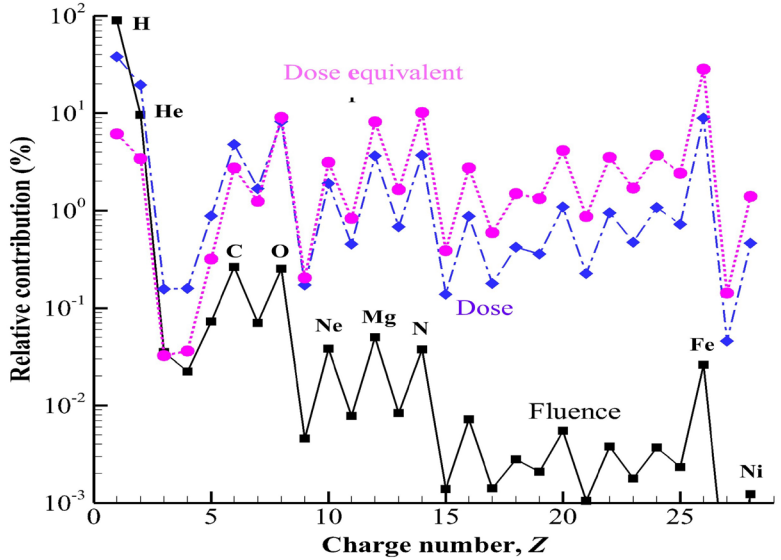
[Images adapted from NASA.gov]

Galactic Cosmic Rays

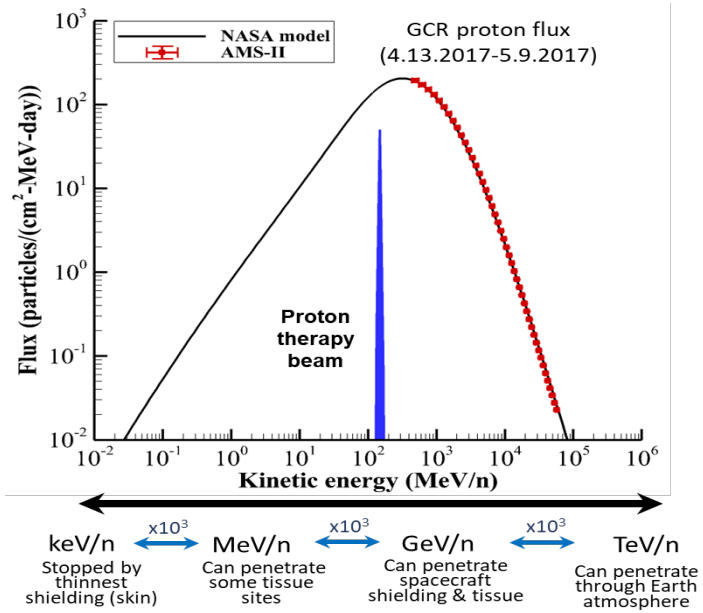
- ***VERY*** different than radiation on Earth → adverse biological affects
  - Highly penetrating, complex mixed field including protons and heavier nuclei
    - protons (85%), helium ions (12%)
    - high charge and energy (HZE) ions (1%) (lower flux but biologically significant)
  - Chronic low-dose rate exposure that varies with solar cycle
  - GCR velocities approach the speed of light



- Able to penetrate shielding and human tissue → Difficult to shield with current technologies



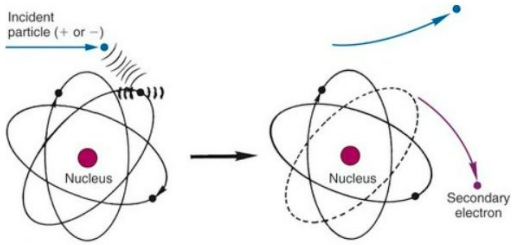
Relative contributions of different elements for1976 solar minimum GCR environment [Simonsen, Slaba, Guida, (2020)]



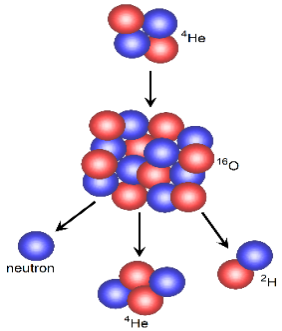
[Image courtesy of Tony Slaba]

Interactions of GCR Particles With Matter

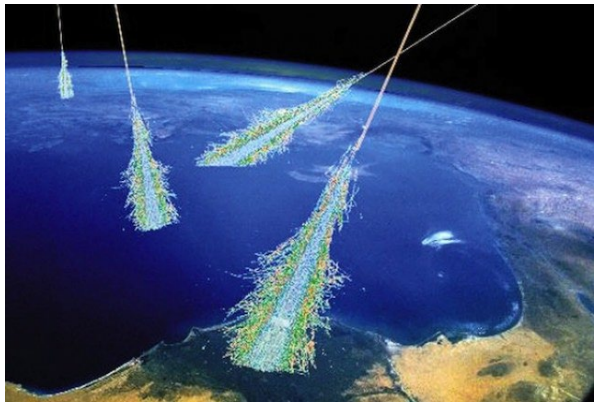
- As GCR particles passes through matter (shielding and/or tissue), physical interactions modify the original particles and may result in the production of secondary particles
  - Combination of atomic and nuclear interactions: energy loss and fragmentation



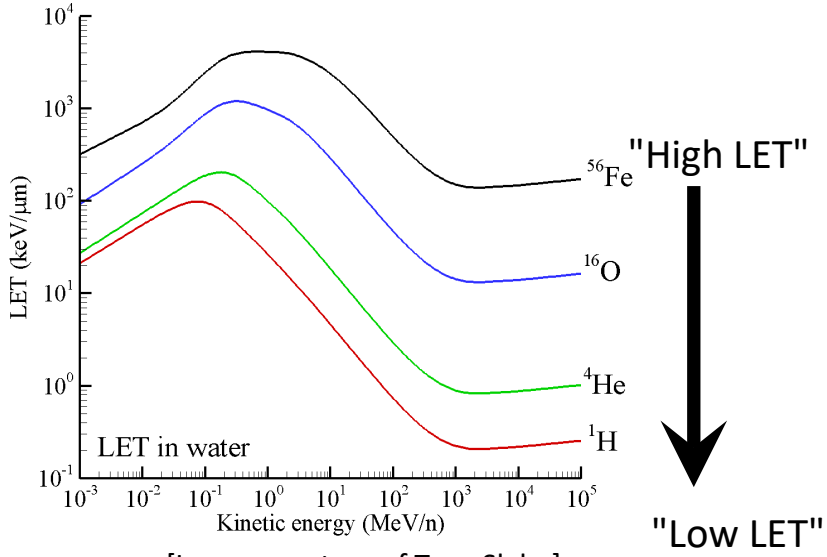
Coulomb interaction with electrons of target material leading to ionization event



Depiction of nuclear interaction between ^{4}He and ^{16}O



Atmospheric cascade resulting from inelastic nuclear collisions [NASA.gov]



[Image courtesy of Tony Slaba]

GCR Simulation

- Ground-based experiments are performed to improve understanding of space radiation-induced health effects
- Previous ground-based studies mainly utilized single mono-energetic beams
  - Collectively improved our understanding of underlying biological mechanisms
  - Incomplete analog for the complete space environment
- The GCR simulator (GCRsim) was developed at the NASA Space Radiation Laboratory to better represent the complex mixed field environment in space
  - Intended to deliver deep space ,shielded tissue environment to biological targets in a laboratory setting
  - Includes particles between Z = 1 and Z = 26
  - Covers broad energy range relevant to human health effects
  - Can be delivered in approximately 1 hour!

NASA's NSRL facility in Brookhaven, NY

GCRsim Development Timeline

NSRL PROGRESS

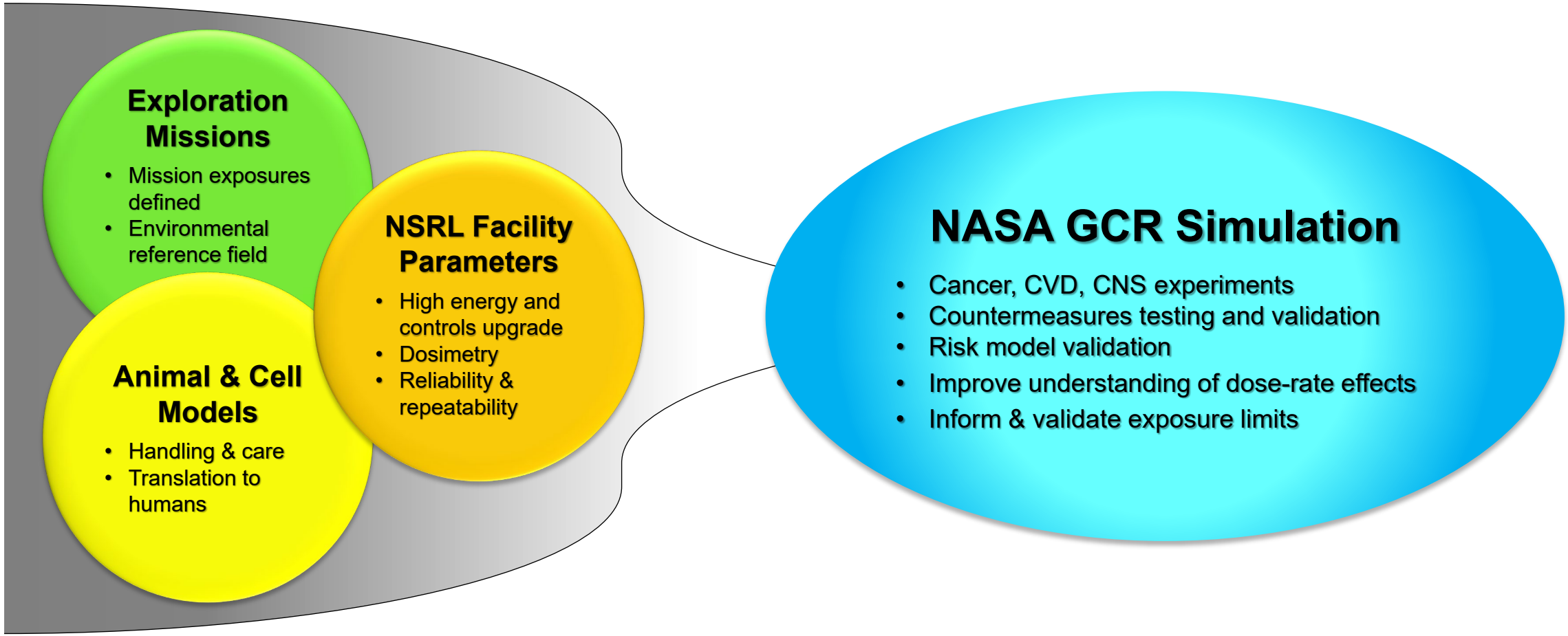
	Prior to GCRsim	Limited and varied mixed-field studies
Utilize LIS as source for ions with EBIS	Mar. 2014	Initial modeling studies on GCR reference field, NSRL constraints, and animal considerations
	Oct. 2014	**Preliminary GCRsim workshop at LaRC to consult with research (physics & biology) community and NSRL**
	Jan. 2015	2015 IWS session – initial concept and considerations along with open discussion and panel Q&A
	Jan. 2016	2016 IWS: GCR consortium formed and first meeting held (Kronenberg, Hada, Blakely/Chang)
Demonstrate 3 ion day	Feb. 2016	Norbury et al. LSSR opinion paper – summary of discussion with international research community Slaba et al. LSSR technical paper – summary of modeling and analysis results to date
	Feb. 2017	*Completed HRP action to define baseline GCRsim*
Test NSRL dosimetry system to deliver small dose packets	Sep. 2017	GCRsim commissioned for use
	Aug. 2018	Established concept of operations for animal handling
	Oct. 2018	First 4-week GCRsim – 3 PI-led teams
	Dec. 2019	Simonsen et al. PlosBiology paper – documenting NASA GCRsim
	Dec. 2020	**GCRsim virtual workshop to discuss mixed-field definition**
	TBD	Dose-rate issues in ground-based GCR simulation

Published research community assessment: **GCRsim mixed field is state-of-the-art and suitable for intended purpose!**

[Huff, Poignant, Rahmanian, Khan, Patel, Norman, Simonsen, Slaba et al, *Life Sci. Space Res* **36**:90-104; 2023]

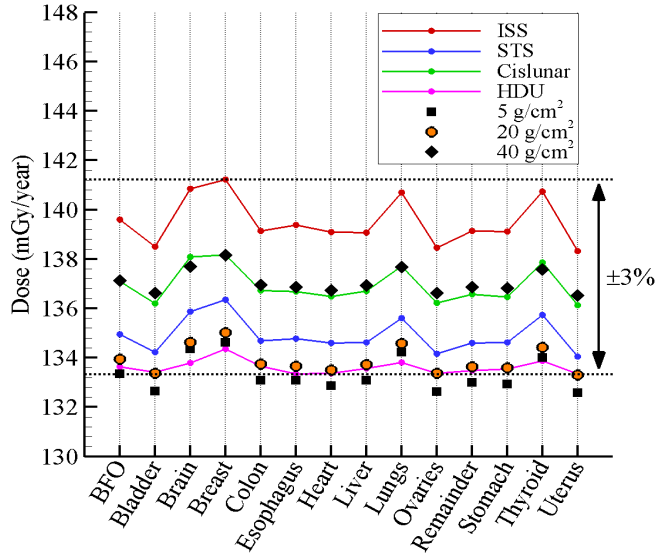
Development of GCRsim at NSRL

- Three key areas developed together to provide the GCR simulator at NSRL.

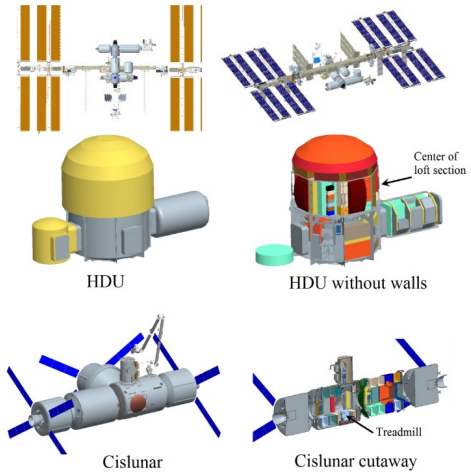


GCR Reference Field

- Shielded tissue field in space depends on several factors
  - Tissue location
  - Shield design
  - Solar activity
- Exposures assessed over a broad range of mission architecture and shielding configurations
- **A single reference field was defined to approximate deep space environment for all missions**
  - Observed variation smaller than uncertainty associated with trying to represent GCR at an accelerator
    - Shielding details have minimal impact on dose (<5%) and moderately small impact on dose equivalent (~15%)
    - Solar cycle variations affect dose-rate but do not qualitatively change the LET spectrum →Solar max spectra can be scaled by ~1.85 to represent solar min



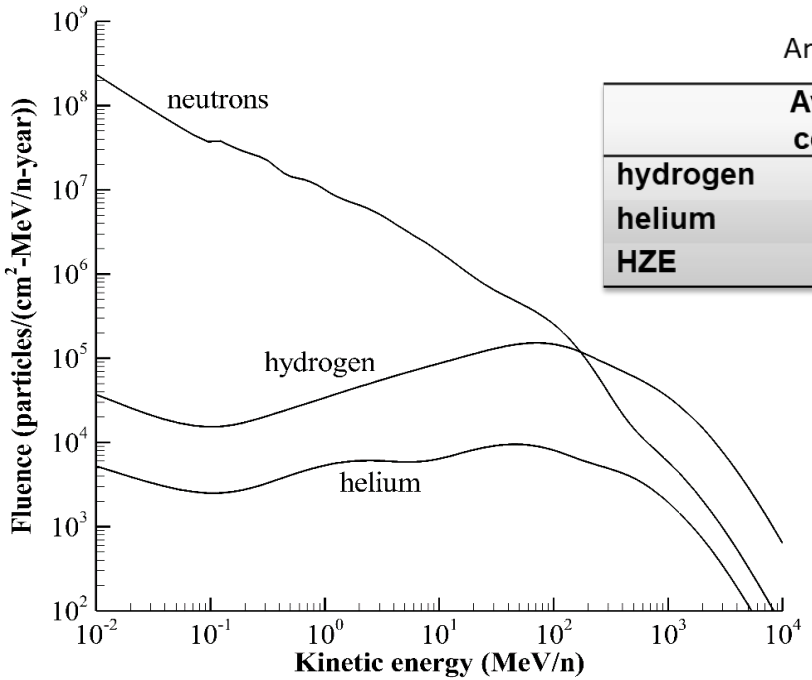
Female tissue dose behind various shielding configurations [Slaba et al. (2016)]



Different Shield designs [Slaba et al. (2016)]

GCR Reference Field

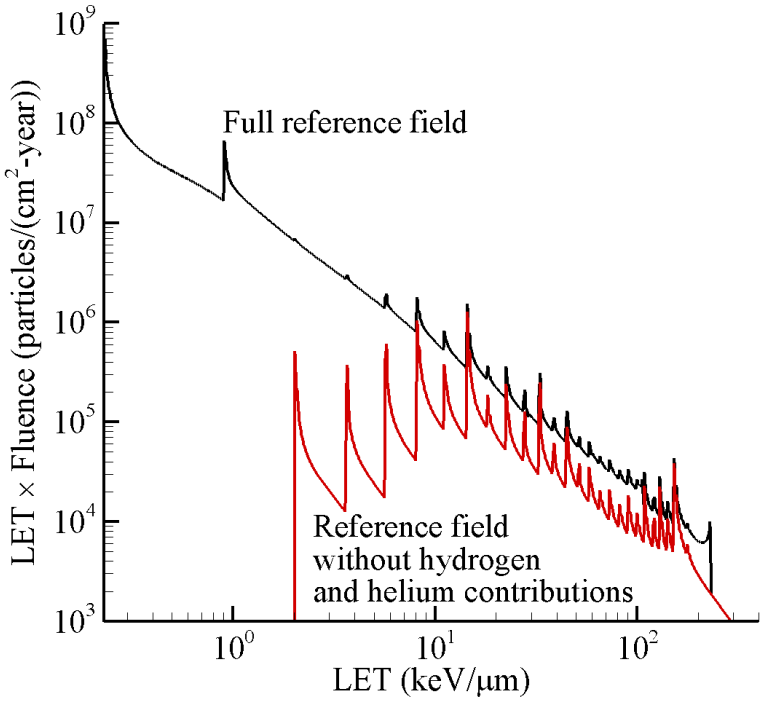
- Female BFO (blood forming organ) was chosen behind 20 g/cm^2 spherical aluminum shielding during solar minimum



Reference field energy spectra for neutrons, hydrogen, and helium [Slaba et al. (2016)]

Annual reference field quantities

	Avg. hits per cell nucleus	Dose (mGy)	Dose Eq. (mSv)
hydrogen	126	86.0	131.1
helium	7	22.5	93.8
HZE	0.5	8.9	73.3

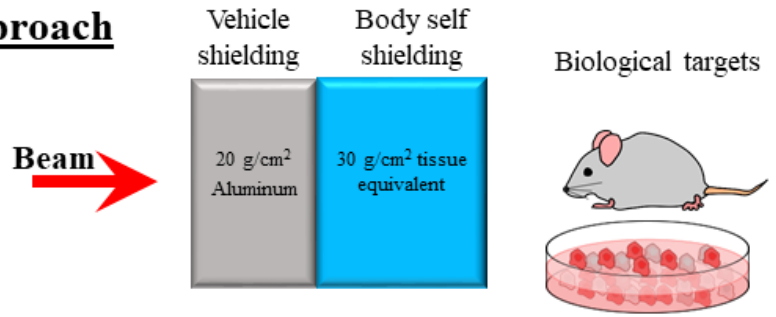


Differential LET spectra of reference field with and without contributions from hydrogen and helium [Slaba et al. (2016)]

GCR Simulation Approaches

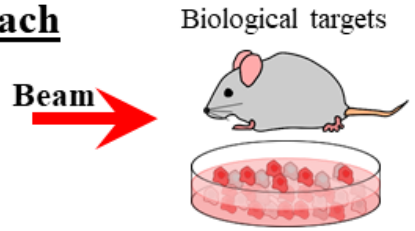
a.) External Field Approach

Beams selected to represent external, free space GCR environment. Representative spacecraft and body self shield material in beam line.



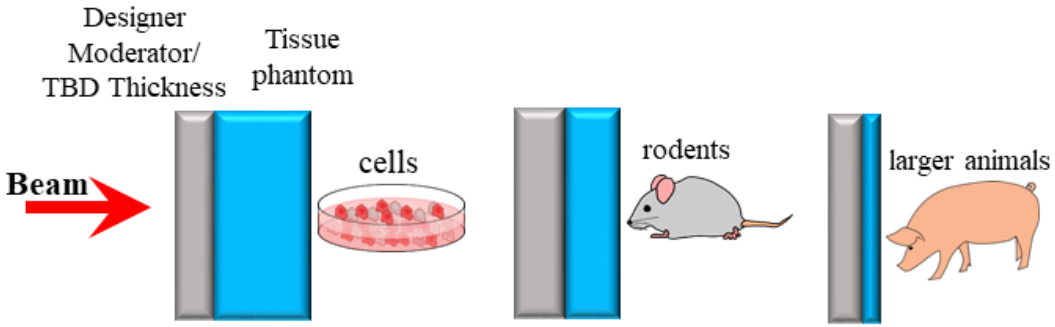
b.) Local Field Approach

Beams selected to directly represent shielded tissue environment.



c.) Hybrid Approach

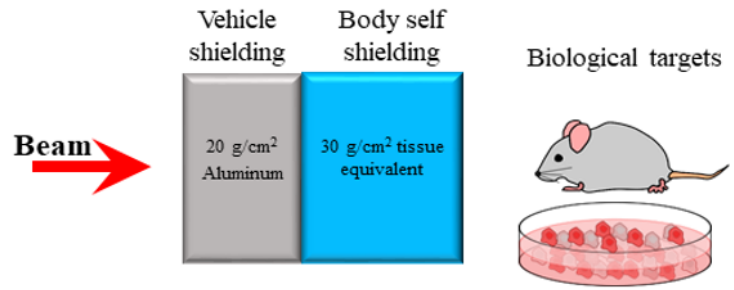
External beams optimized with moderator and variable tissue thicknesses inversely scaled to size of biological sample in beam line to produce spectra of energies and ions.



[Simonsen, Slaba, Guida, Rusek (2020)]

GCR Simulation Approach: External Field

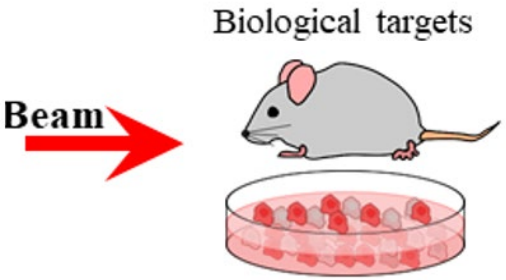
- External free space GCR spectrum with shielding in the beamline
  - Use energetic heavy ion beam such as 1 GeV/n ^{56}Fe
  - Biological target placed downstream from the shield
  - Nuclear reactions produce complex mixed-field behind shielding
  - Energy modulation/broadening via moderator geometry design



- Implementation hurdles for external field approach
  - Required upper energy at NSRL not sufficient for full secondary particle spectrum
    - Neutron spectrum can be produced up to ~1 GeV
    - Pion and electromagnetic cascade will be poorly represented
  - Using large beam for high throughput experiments can be difficult
    - Significant mass (at least ¼ ton) required in beam line
    - Can't just rely on physics model as there is up to a factor of 2 uncertainty for secondary ions production
    - Significant dosimetry requirements
  - No clear means of connecting single-beam and broad mixed-field beam data
    - Difficult to leverage historical single-beam datasets
    - Hinders model development, validation, and interpretation of experimental results

GCR Simulation Approach: Local Field

- Multiple beams are selected to collectively represent the shielded tissue radiation environment
  - Models are used to assess the radiation environment encountered by astronauts
  - Sequentially irradiate biological target with selected beams



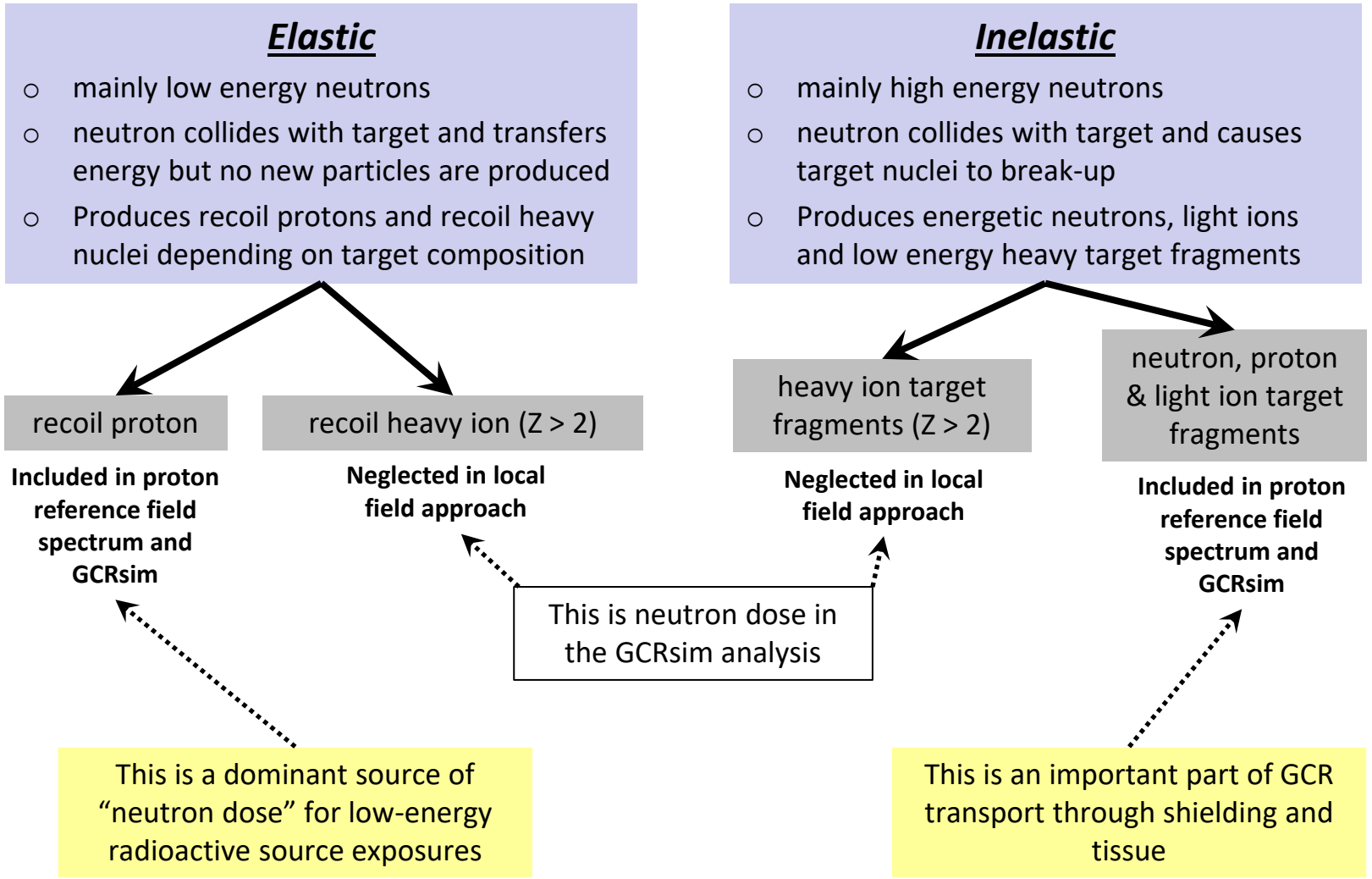
- **Local field approach was chosen at NSRL because of its advantages**
  - NSRL energy limits able to cover relevant range
    - Covers 90% of the effective dose vs. 60% for the external approach
  - Current dosimetry system can be used with minimal modification (and cost)
  - Can be designed to leverage historical datasets
  - Can be designed (and modified) to support multiple animal species
- Disadvantages to local field approach
  - Lack secondary neutrons (sort of), pions, and electromagnetic cascade components
  - Breaks spatial and temporal correlations between tracks generated by HZE interactions
  - Sequential delivery of single beams *may* not give same biological result as a true mixed field

Can possibly be addressed with hybrid solutions in the future

Neutron Contribution in the Local Field Approach

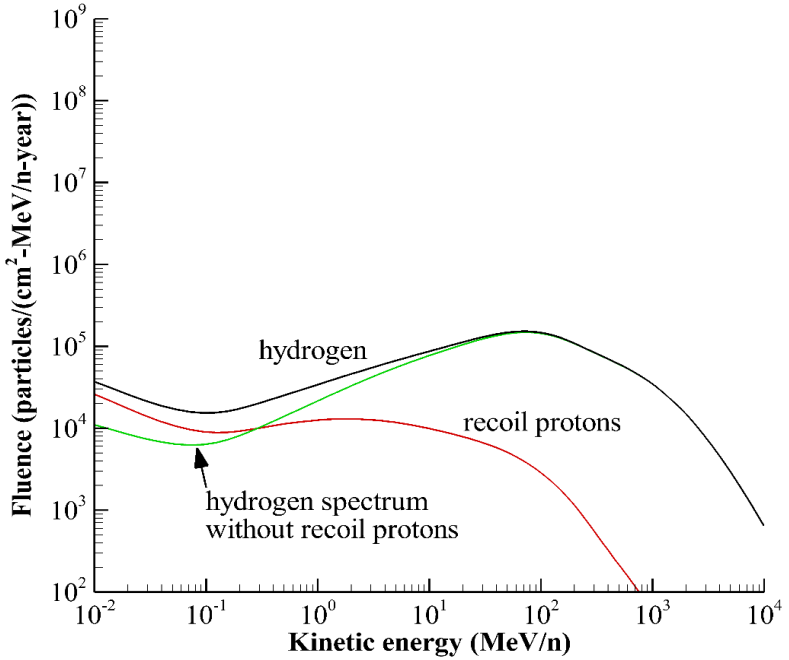
- Main components of "neutron dose" ***are*** included in GCRsim
  - Proton recoil
  - Nucleon and light ion target fragments

- GCRsim beam neglects heavy ion target fragments and heavy recoil
  - Low energy (< 10 MeV/n)
  - High LET (> 300 keV/µm)

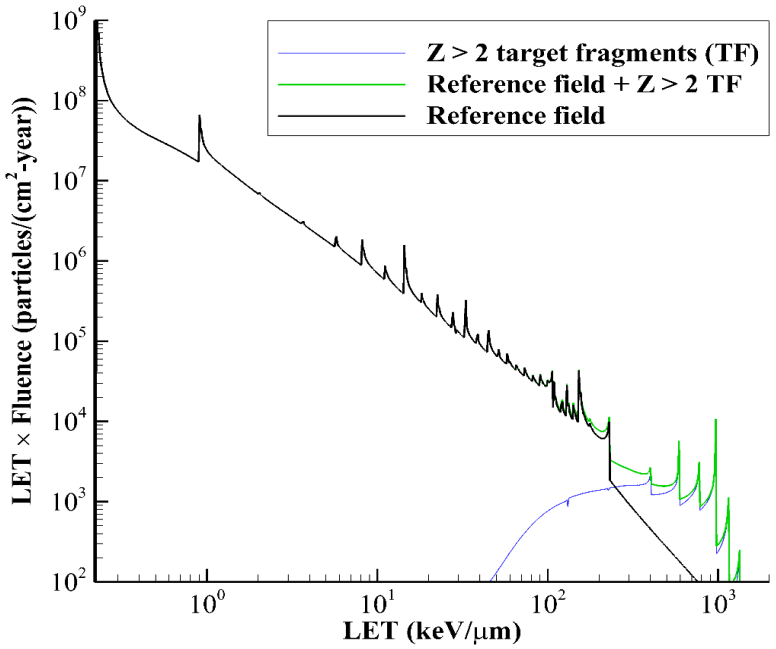


Neutron Contribution in the Local Field Approach

- Protons (& light fragments) produced from *inelastic* neutron reactions are **included** in GCRsim reference field
- Recoil protons from *elastic* neutron collisions are **included** in the GCRsim reference field
  - Low energy beam intensities obtained from reference field spectrum

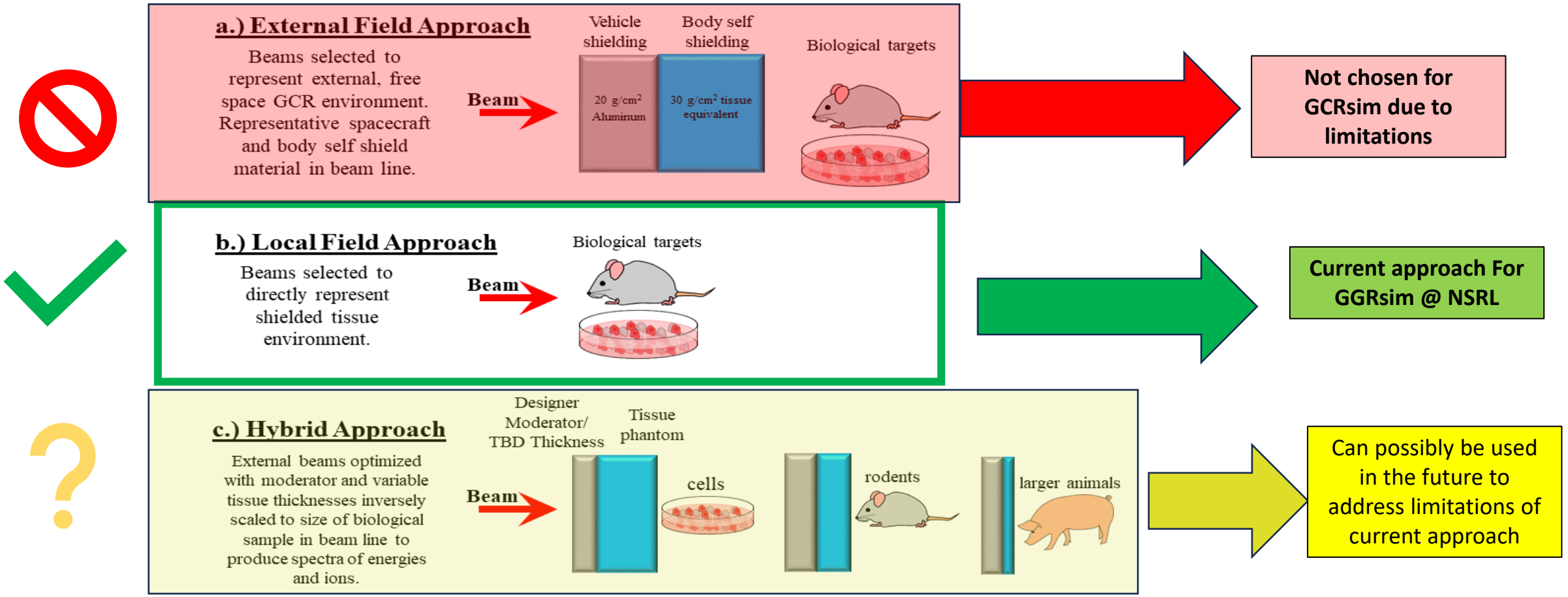


- Z > 2 target fragments and recoils from neutrons are **not included** in GCRsim beam
  - Average energies of <10 MeV/n
  - Only contribute to fluence above 300 keV/µm
  - Would be difficult to represent in any ground-based simulator using animal models (even harder in cell models)



[Slaba et al. (2016)]

Current Simulation Approach For GCRsim



GCR Beam Definition at NSRL

- 33 mono-energetic beams of varying energies and ion species
  - 4 H energies plus degrader (65-75% dose)
  - 4 He energies plus degrader (10-20% dose)
  - 5 Heavy ions: C, O, Si, Ti, Fe (6-8% dose)
- Sequential beam delivery reproducing the shielded tissue environment in deep space over the full range of LET
- Requires ~1 hour to deliver

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	100	*Polyethylene degrader to*		
^{1}H	150	15.9	0.54	35.0
^{1}H	250	38.1	0.39	68.9
^{1}H	1000	326.6	0.22	123.6
^{4}He	100	*Polyethylene degrader to*		
^{4}He	150	16.0	2.17	7.5
^{4}He	250	38.3	1.56	16.4
^{4}He	1000	327.8	0.88	24.9
^{12}C	1000	110.1	7.95	11.7
^{16}O	350	17.0	20.8	15.4
^{28}Si	600	22.7	50.2	8.1
^{48}Ti	1000	32.5	109.5	4.5
^{56}Fe	600	13.1	175.1	4.1
Total				***500.0***

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	20.0	0.43	2.59	30.4
^{1}H	23.3	0.56	2.29	6.7
^{1}H	27.2	0.75	2.02	7.4
^{1}H	31.7	0.98	1.79	8.0
^{1}H	37.0	1.30	1.58	8.7
^{1}H	43.2	1.72	1.39	9.3
^{1}H	50.3	2.26	1.23	10.0
^{1}H	58.7	2.99	1.09	10.6
^{1}H	68.5	3.95	0.97	11.1
^{1}H	79.9	5.20	0.86	11.2
^{1}H	100.0	7.76	0.73	**27.2**

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{4}He	20.0	0.43	10.34	**11.0**
^{4}He	23.3	0.57	9.14	**2.1**
^{4}He	27.2	0.75	8.06	**2.2**
^{4}He	31.7	0.99	7.12	**2.3**
^{4}He	37.0	1.31	6.29	**2.5**
^{4}He	43.2	1.73	5.56	**2.6**
^{4}He	50.3	2.28	4.92	**2.7**
^{4}He	58.7	3.01	4.36	**2.7**
^{4}He	68.5	3.97	3.86	**2.7**
^{4}He	79.9	5.23	3.43	**2.7**
^{4}He	100.0	7.81	2.90	**6.1**

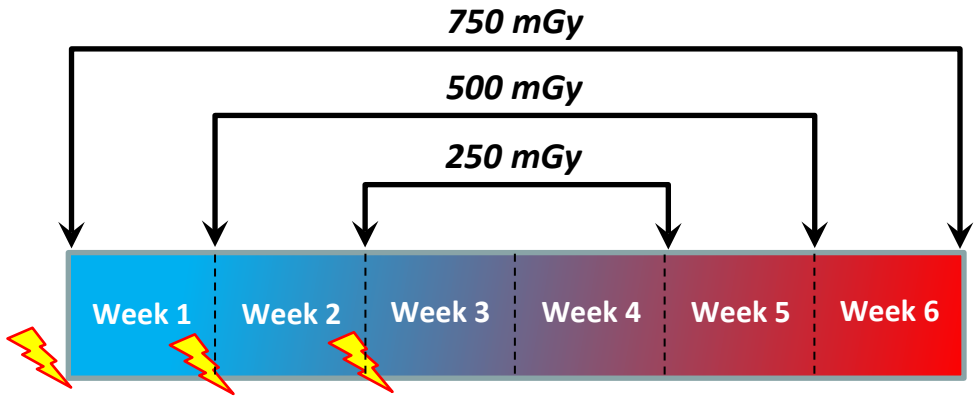
[Simonsen et al. (2020)]

Order of GCRsim Beam

- GCR environment is generally thought of as a continuous shower of protons with interspersed helium and sporadic heavy ions
- Ordering of GCRsim beams is defined to approximate this behavior to the extent possible
  - Frequent delivery of protons and helium
  - Sporadic heavy ions throughout the sequence
  - Major components of proton/helium dose are delivered first and last
- Protracted GCR exposures over 2-6 weeks
  - Full GCRsim beam (33 ions) delivered daily
  - NSRL can deliver full GCRsim beam in ~1 hour
  - Beam delivered 6 days per week to allow for contingencies

GCR simulator beam ordering

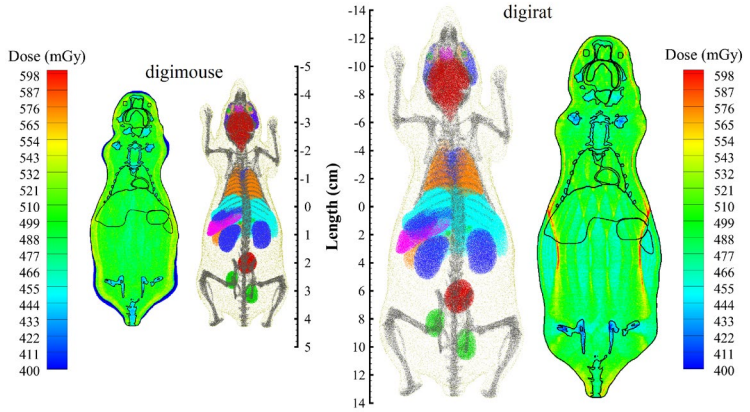
(H 1,000), (He 1,000), **(Si 600)**
(H 20), (H 23), (He 20), (He 23), **(Ti 1,000)**
(He 27), (He 32), (H 27), (H 32)
(H 37), (H 43), (He 37), (He 43), **(O 350)**
(He 50), (He 58), (H 50), (H 58)
(H 68), (H 80), (He 68), (He 80), **(C 1,000)**
(He 100), (H 100), (H 150), (He 150), **(Fe 600)**
(He 250), (H 250)



Internal Exposure Verification for Animal Models

- Need to verify an important assumption of the GCRsim
  - GCRsim beam can represent the reference field inside radiosensitive organs for animal model experiments

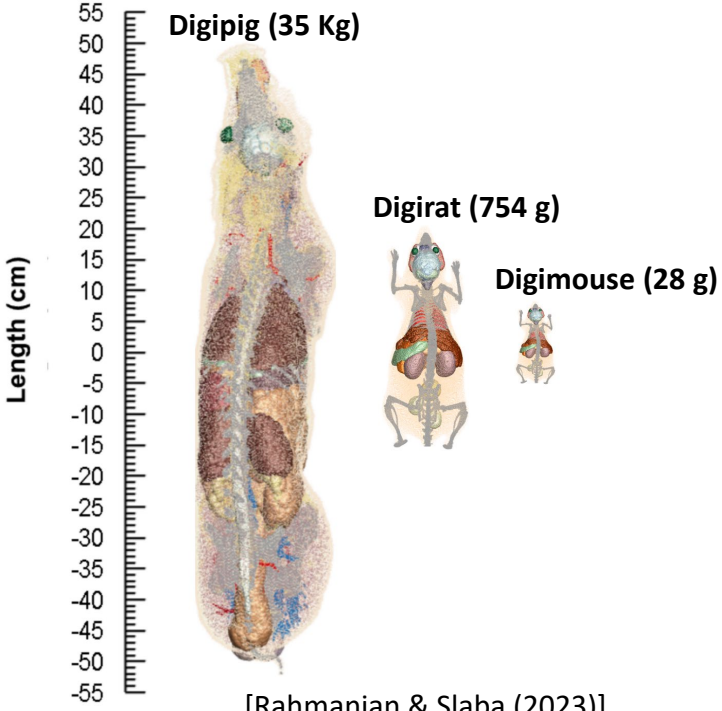
Reference field (shielded tissue environment in space)	≈	**GCRsim beam exposure** (cell exposure)	≈	**Internal Exposure from GCRsim** (radiosensitive organs of the animal model)



[Simonsen, Slaba, Guida, Rusek (2020)]

- Initial verification performed with Monte Carlo transport simulations coupled to
  - Simplified ellipsoidal water phantoms
  - 3D voxelized digital phantoms of mouse (Digimouse) and rat (Digirat)
  - **→ GCRsim is applicable for both mouse and rat models**

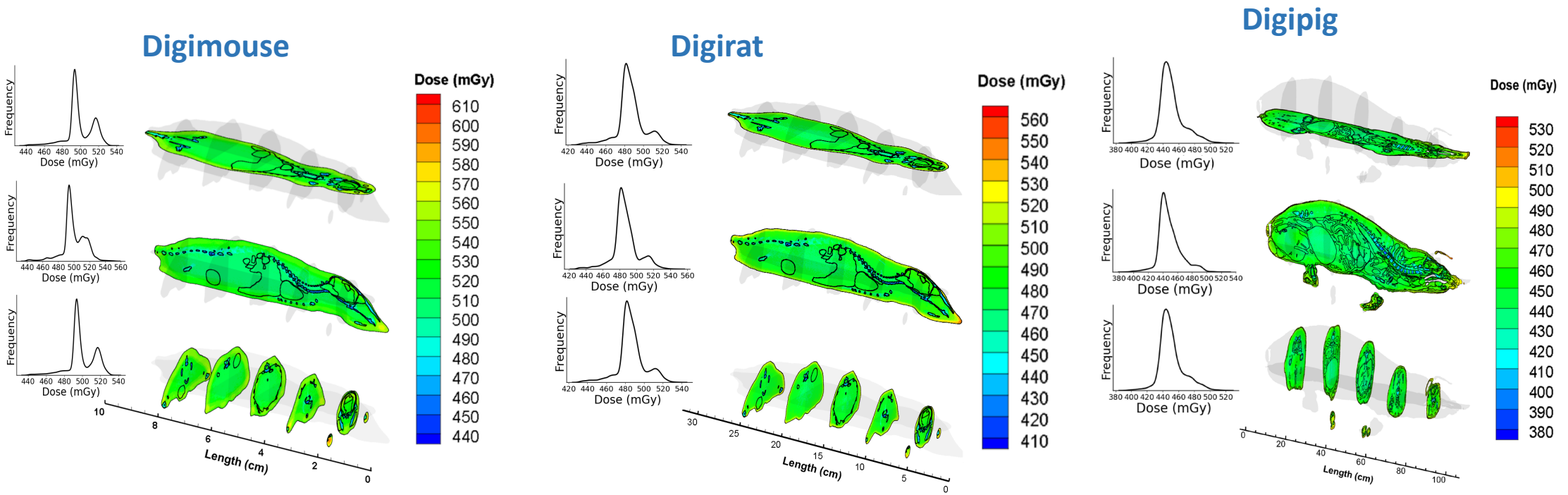
- More comprehensive verification recently completed to test the applicably of larger animals such as minipig in comparison with the rodent models
  - Minipig tissue shielding is much greater than rat or mouse shielding
  - Need determine if the additional tissue shielding modifies GCRsim beam beyond intended purposes



[Rahmanian & Slaba (2023)]

Internal Exposure Verification for Animal Models

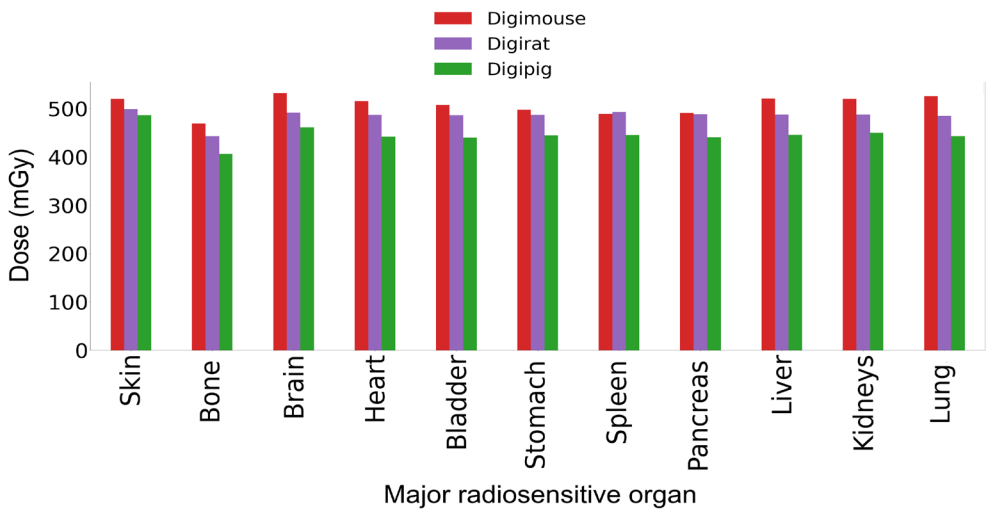
- Internal dose is relatively homogeneous in all three animal models
  - Voxel dose variation <10% at a 95% confidence level (i.e. 95% of voxels tallied)
  - Slightly higher doses observed in outer skin layer
  - Homogeneous doses in brain, heart, and radiosensitive tissues



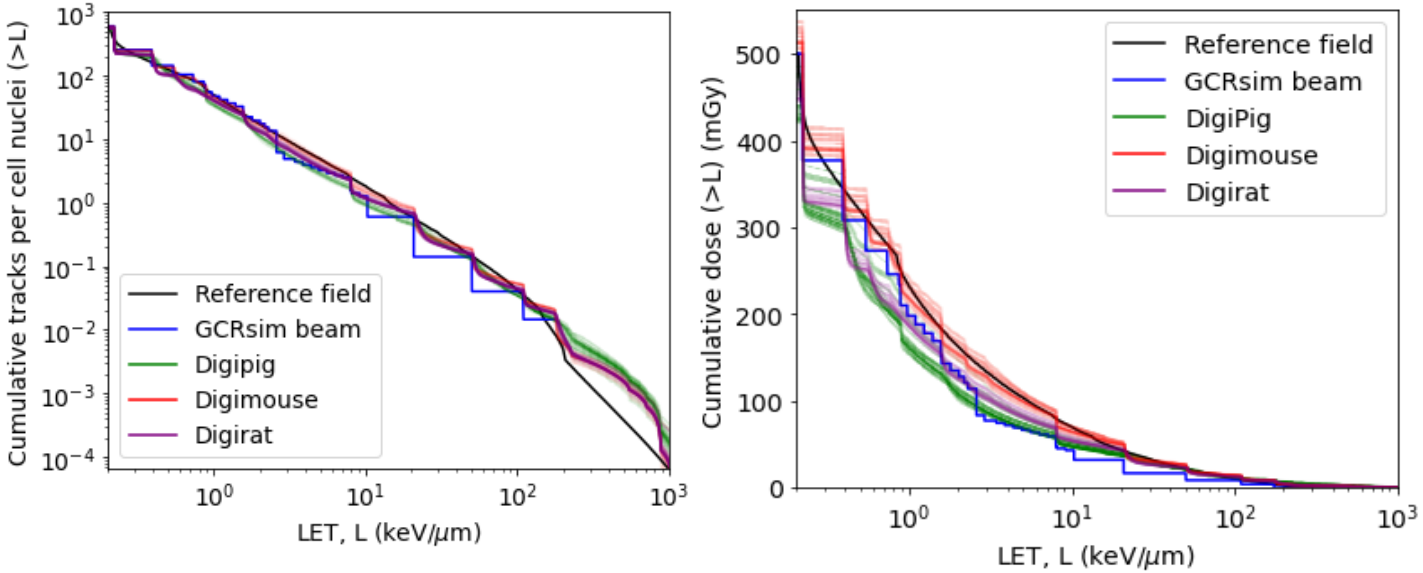
Simulated internal dose profiles for Digipig, Digirat, Digimouse exposed to isotropic 500 mGy GCRsim beam [Rahmanian & Slaba (2023)]

Internal Exposure Verification for Animal Models

- Radiosensitive tissue doses are homogeneous across all three animal models
  - All soft tissue doses were within 10% of the beam dose
- Spectral characteristics of reference field are maintained within all three animal models models
  - Important to verify that “cell hits” (fluence) and dose as a function of LET are maintained
  - LET region below 10 keV/um accounts for 99% of fluence and 86% of dose



Side by side comparison of simulated dose in major radiosensitive organs of Digimouse, Digirat and Digipig.



Comparison of the cumulative fluence (on the left), and cumulative dose (on the right) as a function of LET within radiosensitive organs of the three different animal phantoms

[Rahmanian & Slaba (2023)]

Simplified GCR Simulator

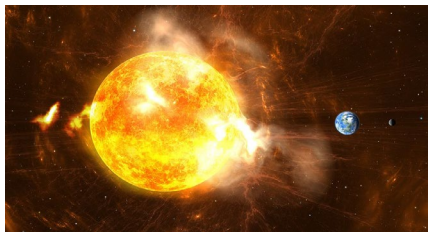
- NASA developed a simplified 5 ion GCR Simulator for collection of preliminary data, countermeasure screening studies, and initial understanding of mixed-field effects
  - Intended for users who do not need the entire GCR spectrum
- 6 monoenergetic beam (5 different ions)
  - 2 H energies (~74% dose)
  - 1 He beam (~18% dose)
  - 3 Heavy ions: O, Si, Fe (~8% dose)
- The beam combination reduces delivery time while dose order and fractions are similar to the full GCRsim.
- Some spectral characteristics of low-energy H and He are lost but still can deliver uniform dose due to long range of these low-energy ions

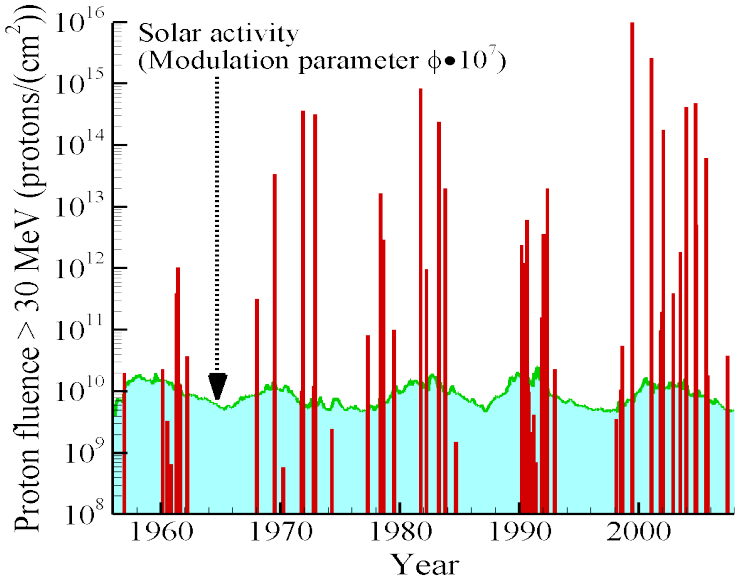
Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	1000	326.6	0.22	174.1
^{28}Si	600	22.7	50.2	5.7
^{4}He	250	38.3	1.56	90.2
^{16}O	350	17.0	20.8	29.1
^{56}Fe	600	13.1	175.1	5.1
^{1}H	250	38.1	0.39	195.9
Total				***500.0***

[Simonsen, Slaba, Guida, Rusek (2020)]

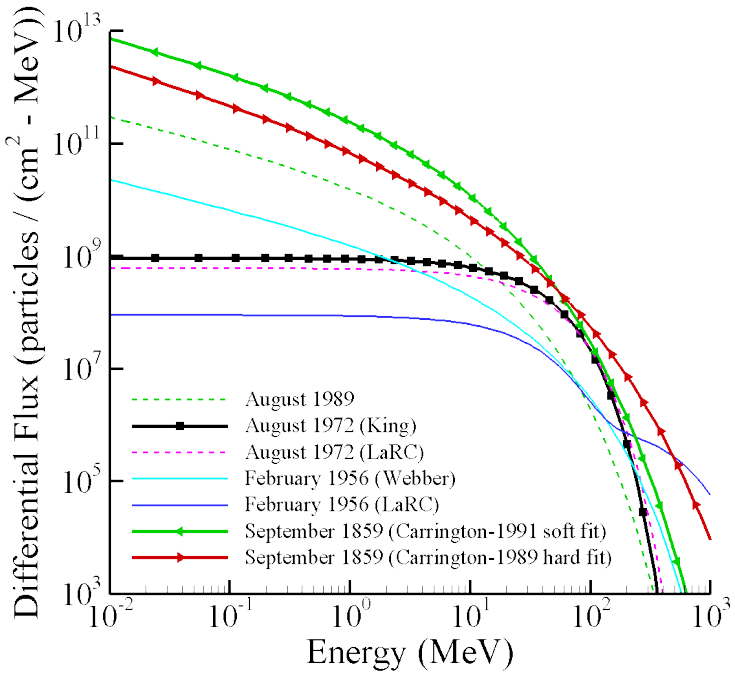
Solar Particle Events

- Solar particle events (SPE) are another component of deep space radiation
- Medium to high-energy protons from coronal mass ejections and solar flares (intense burst protons from the Sun)
  - Energies up to several hundred MeV (may extend up to GeV)
  - Intermittent exposure, difficult to predict occurrence, spectral shape, or magnitude
  - More likely to occur during periods of heightened solar activity (solar max)





Integral proton fluence (E > 30 MeV) for SPEs from 1956 – 2007 [Courtesy of Tony Slaba]

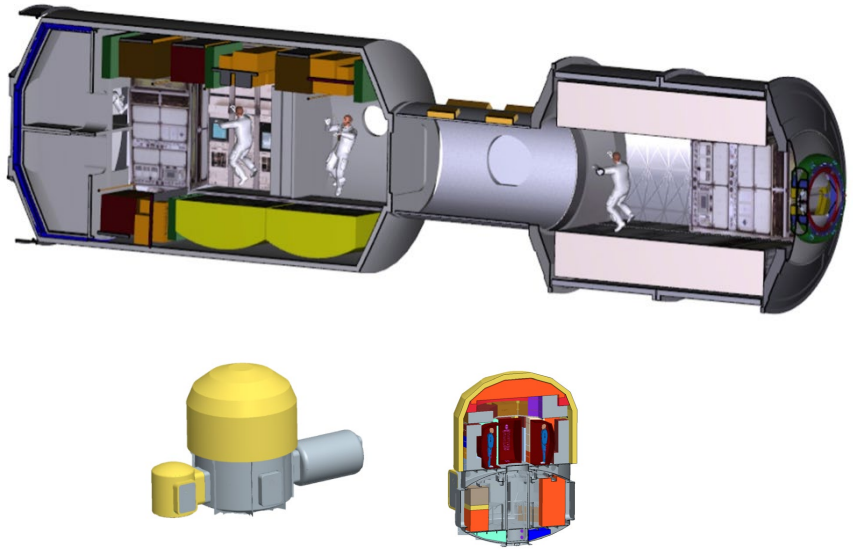


[NASA.gov]

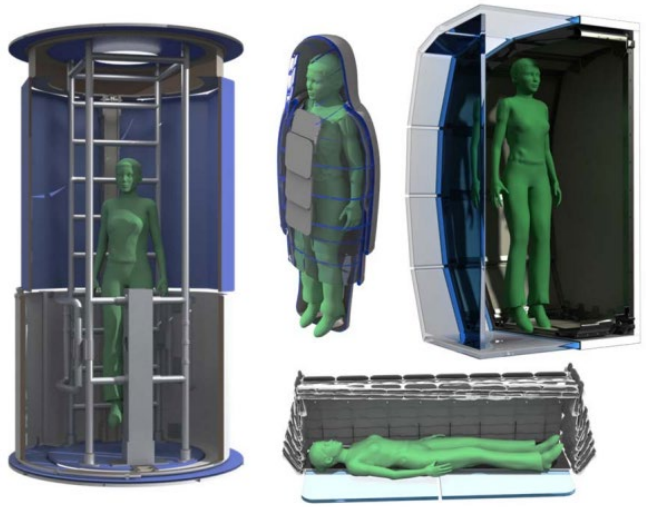
Historical solar particle events [Courtesy of Tony Slaba]

Solar Particle Events

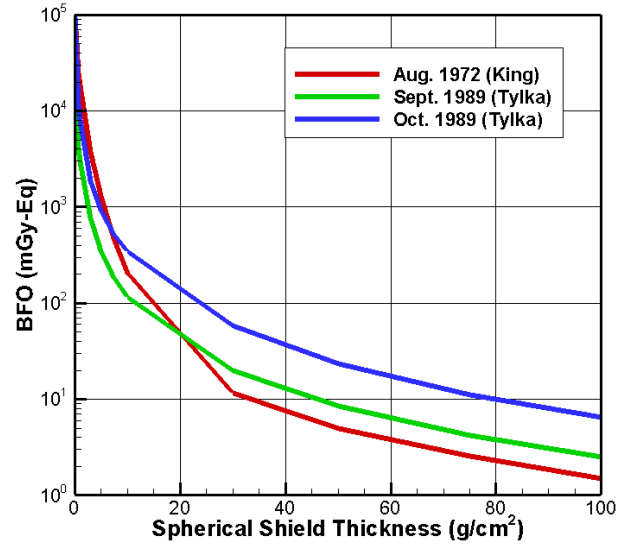
- SPE present serious acute risk to astronauts if not adequately shielded
  - Shielding optimization strategies can mitigate acute radiation responses
    - Risk is sufficiently reduced, and over the course of a long duration mission, the GCR exposure becomes the main concern
  - Some biological uncertainty related to dynamic dose rates, inhomogeneous dose distributions, and impact of combined SPE and chronic GCR on immune function
  - Current SPE protection strategies deemed acceptable by NASA despite biological uncertainties



Habitat designs for radiation protection [Nasa.gov]



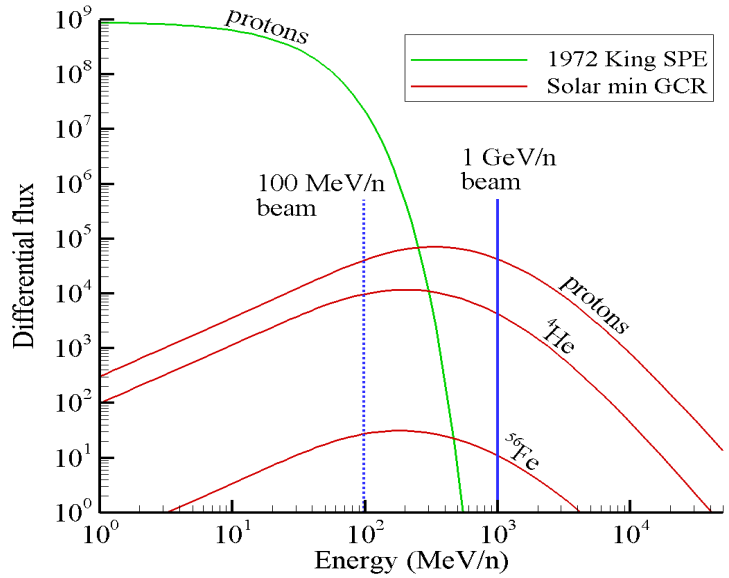
Storm Shelter Concepts to protect astronauts from SPE [Simons and Clowdsley (2013)]

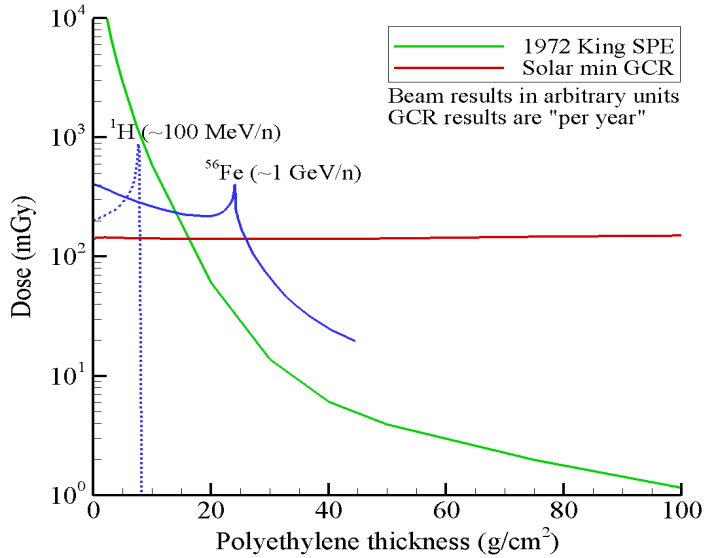


Shielding effectiveness for 3 SPE events [Courtesy of Martha Clowdsley]

SPE vs GCR vs Monoenergetic Beam

- Substantial differences between SPE, GCR, and beam energy spectra
  - GCR energies peak near 300 MeV/n and extend up to several hundred GeV/n
  - SPE energies fall off rapidly after 100 MeV for the 1972 event
  - Very intense (high flux) spectrum at lower energies for SPE
- Substantial differences between dose-depth profiles for various environments
  - SPE dose is very large with minimal shielding but falls off rapidly
  - GCR dose remains relatively flat as a function of polyethylene thickness
  - Beam doses show characteristic Bragg peaks dependent on ion charge and energy

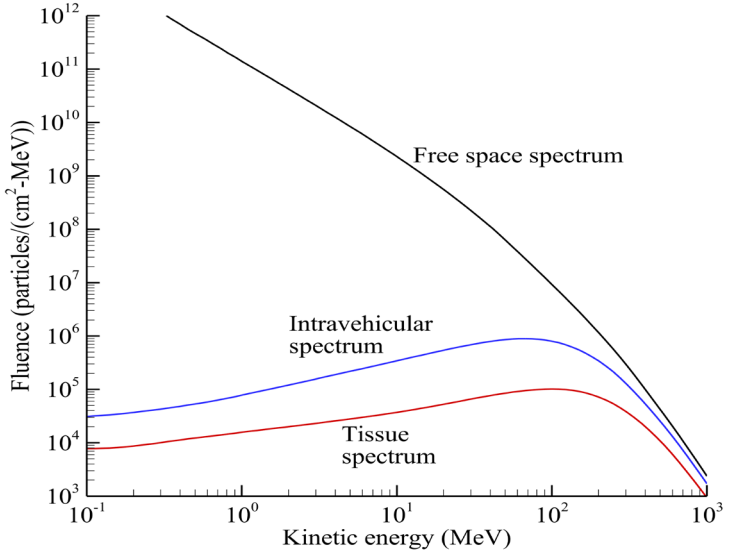




[Image courtesy of Tony Slaba]

SPE simulator at NSRL

- NSRL has a SPE simulator (SPEsim) based on the fluence of the August 1972 event
- The default SPEsim begins with 50 MeV protons, which amounts to 90.26% of the total dose. Then the beam energy increments in steps of 10 MeV up to 150 MeV where 0.15% of the total dose is delivered
- The default SPEsim at NSRL represents the free space spectrum and differs from shielded tissue environment that astronauts will be exposed to
- Currently no SPEsim definition for shielded tissue environment appropriate for biological experiment similar to GCRsim
  - Shielded SPE spectrum is very different from ambient SPE
  - Due to low range of protons, animal and cell models will see a different profile than human would see
  - Depending on the endpoint, and the experimental model used (cells, animals) the SPE spectrum needs to be modified to match dose profile of interest
  - Further modelling is required to support experimental design



Proton fluence spectra for the October 1989 SPE in deep space and shielded environment [Courtesy of Tony Slaba]

Proton energy (MeV/n)	Dose Fraction
50	90.26%
60	2.88%
70	2.00%
80	1.49%
90	1.04%
100	0.80%
110	0.54%
120	0.36%
130	0.28%
140	0.20%
150	0.15%

Default SPEsim beam at NSRL

For tissue and animal experiments need a different beam definition to represent SPE dose profile within internal organs

Summary

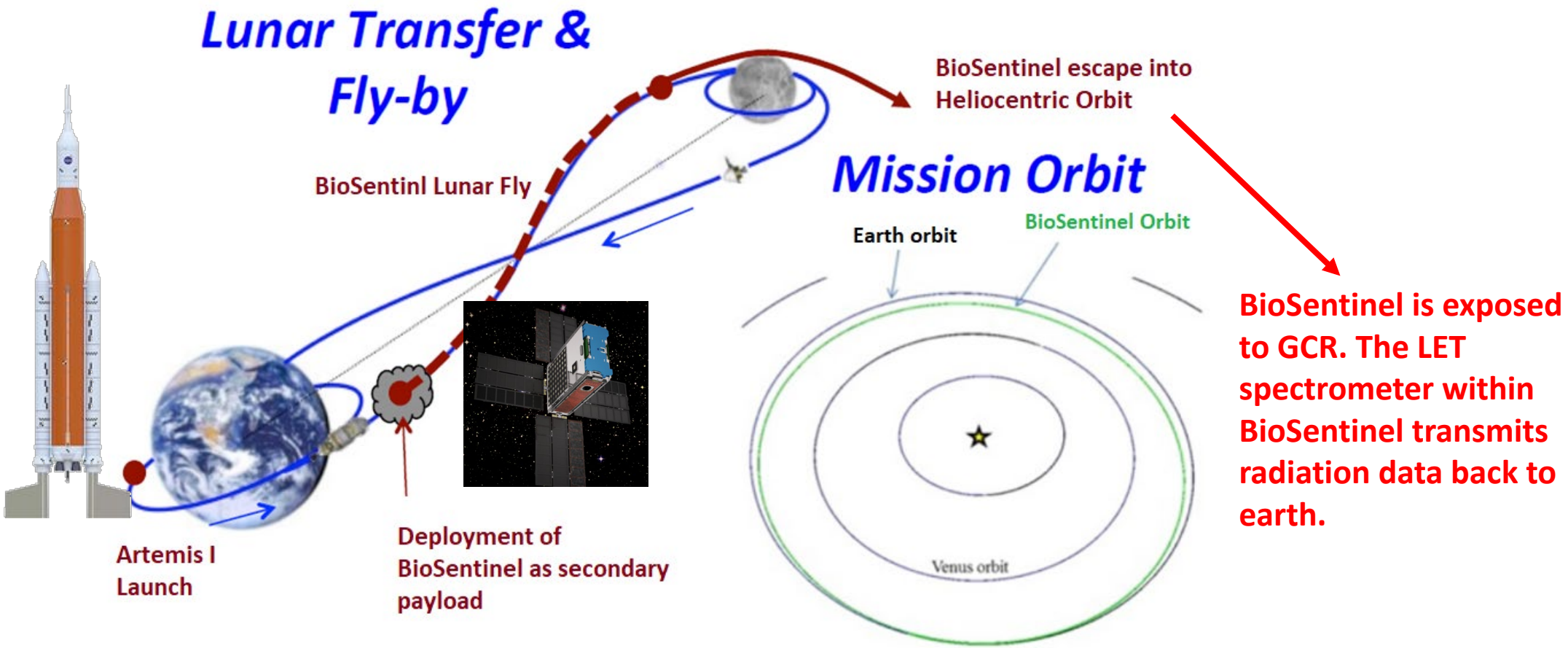
- The deep space radiation environment includes SPE and GCR
  - SPE are intense, unpredictable bursts of low to medium energy protons
  - GCR are continuous background of complex energetic mixed field
- For long duration missions, GCR are the main biological risk
  - SPE pose an acute risk if adequate shielding and ops controls are not provided
  - Health risks from GCR include cancer, cardiovascular effects, and damage to the central nervous system
- The GCR simulator at NSRL is intended to deliver deep space, shielded tissue environment to biological targets in a laboratory setting
  - Developed to optimize across space environment characteristics, facility constraints, multitude of biological endpoints and animal care requirements
- The NSRL GCRsim beam accurately reproduces the space radiation environment
  - Research community input used to guide development throughout
  - Exposure characteristics verified with Monte Carlo and high-res animal models
  - Research community evaluated current mixed field definition during 2020 Virtual Workshop
- A simplified GCRsim with 5 beams is also available for users who do not need the full GCRsim beams
- NSRL also provides SPEsim for free space environment
  - However, may need different beam definition if need to study SPE for biological experiments

Modeled vs. Spaceflight Data: BioSentinel Mission

Shirin Rahmanian, PhD

SHINE Practicum

BioSentinel In Deep Space

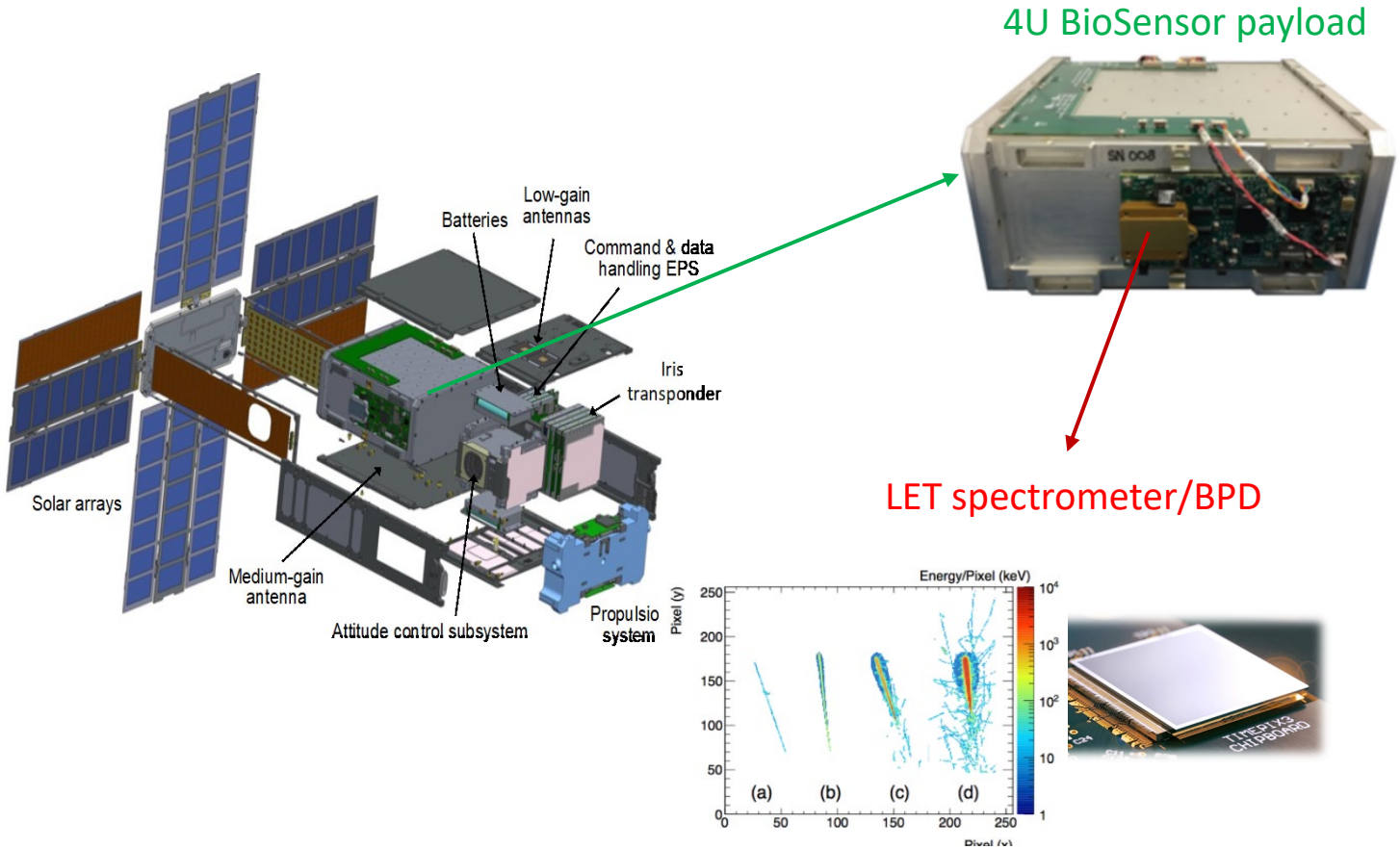


BioSentinel is exposed to GCR. The LET spectrometer within BioSentinel transmits radiation data back to earth.

[Image adapted from NASA.gov]

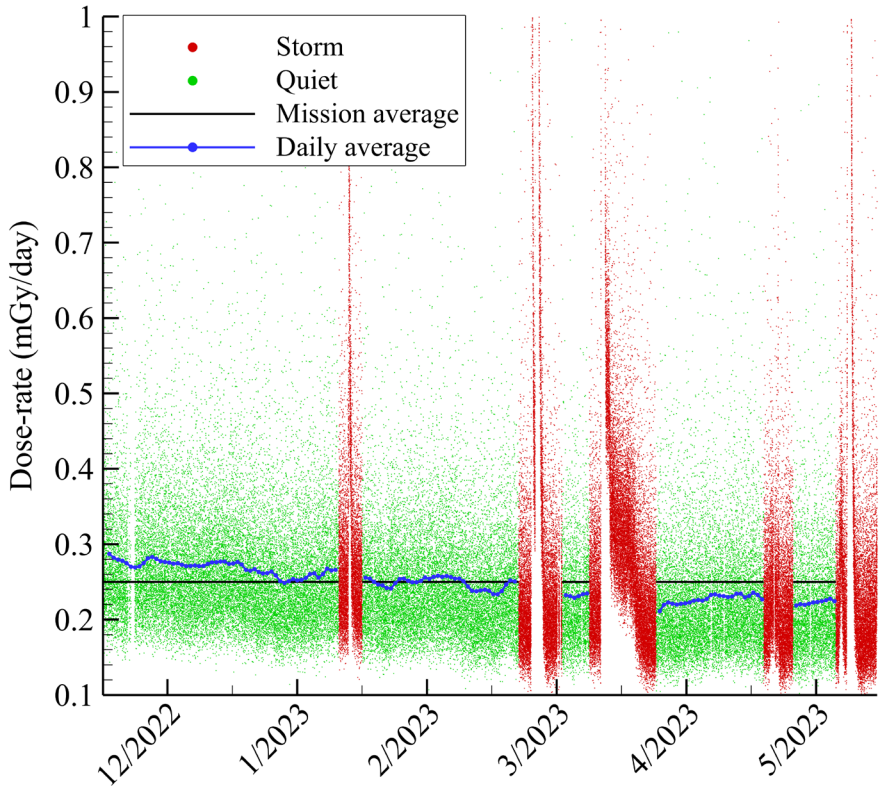
BioSentinel Spaceflight Radiation Measurements

- An LET spectrometer – also referred as BioSentinel Pixel Dosimeter (BPD)- onboard BioSentinel measures space radiation and transmits data to earth
  - Timepix silicon detector located within 1-2 cm of external face of the CubeSat
  - Measure radiation over the 0.2–300 keV/µm LET range
  - Provides dose rate measurements and LET spectra

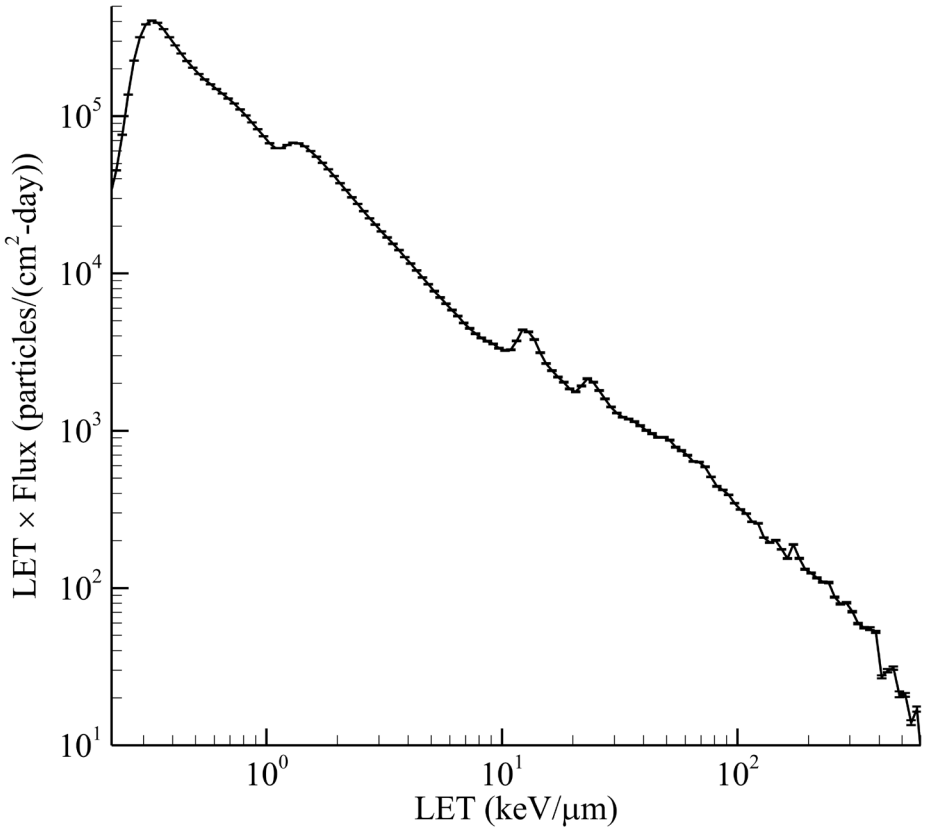


[Image adapted from NASA.gov]

BioSentinel Flight Measurement Data



Minute by minute dose-rate (mGy/day) measurements with BioSentinel Timepix detector



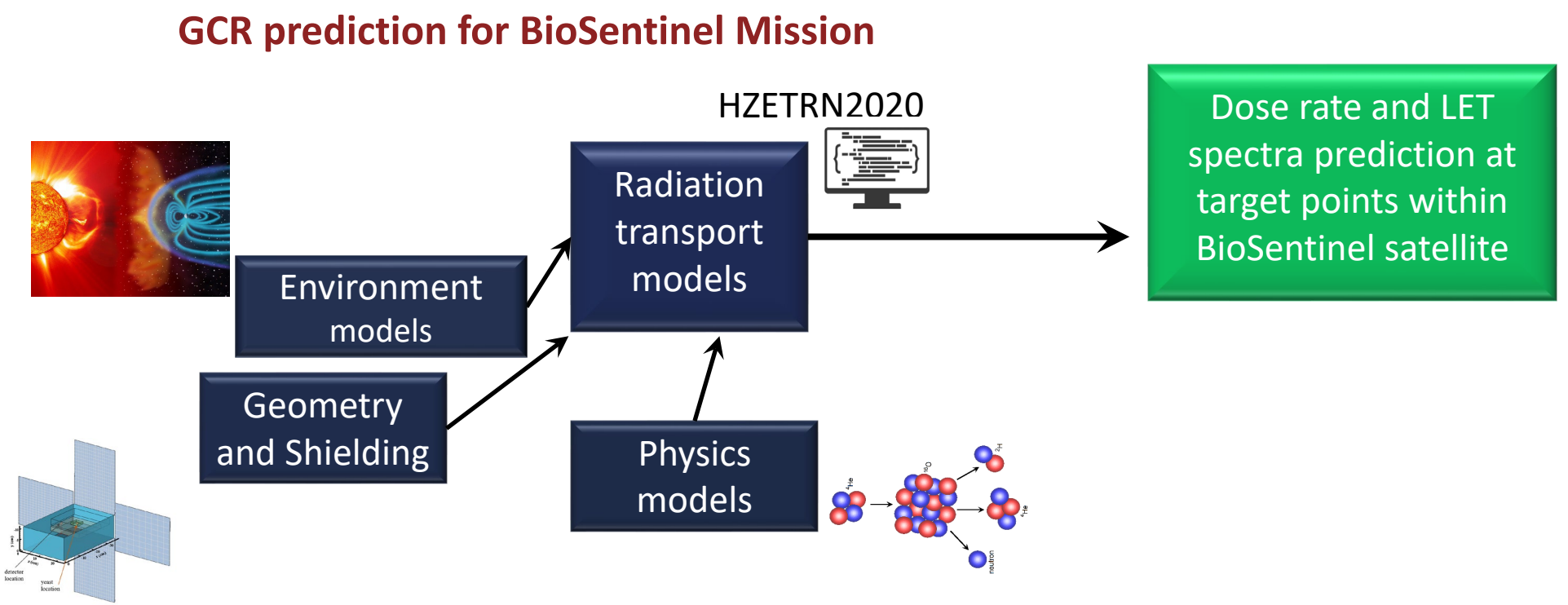
LET spectral measurement for the BioSentinel mission obtained from the LET spectrometer

[Rahmanian, Slaba, George, Braby, Bhattacharya, Straume and Santa Maria. (2024)]

Figures from submitted manuscript : **Please Do Not Disseminate!**

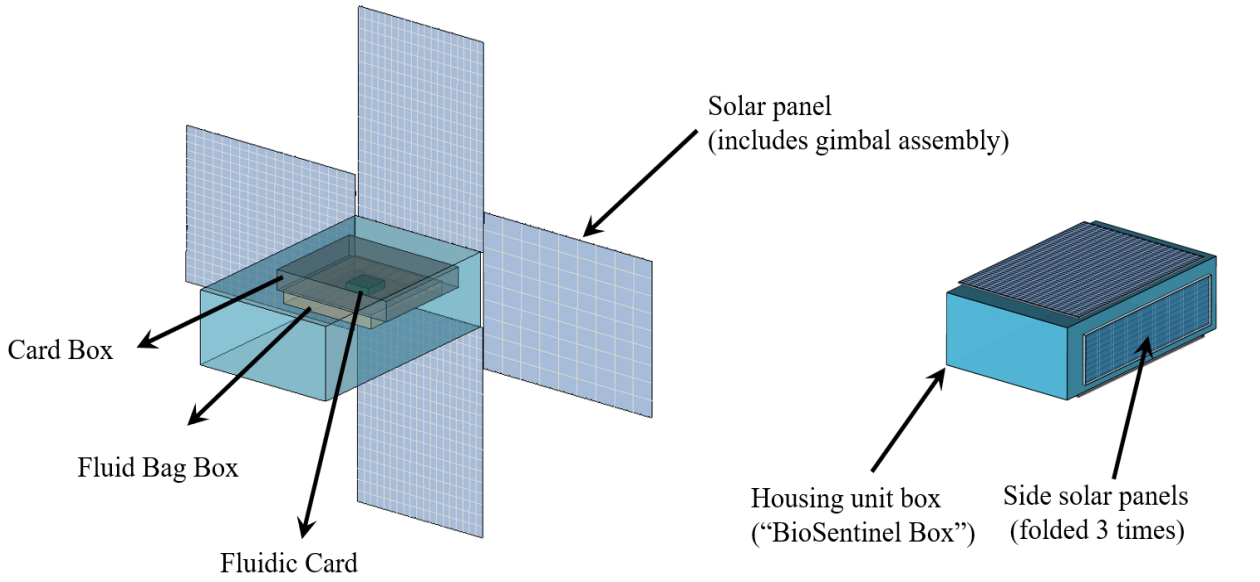
Modeling BioSentinel GCR environment

- GCR environment can be modelled/predicted using combination of environmental and physics models and deterministic radiation transport
  - NASA's HZETRN2020



BioSentinel Geometry Setup in HZETRN

- Combinatorial geometry to describe the BioSentinel mass shielding
  - 8 different components explicitly identified
  - Each component requires material assignments based on estimated composition



Deployed Configuration **Stowed Configuration**

[Rahmanian et al., 2023]

Table1: Components of the BioSentinel for geometry setup in HZETRN2020.

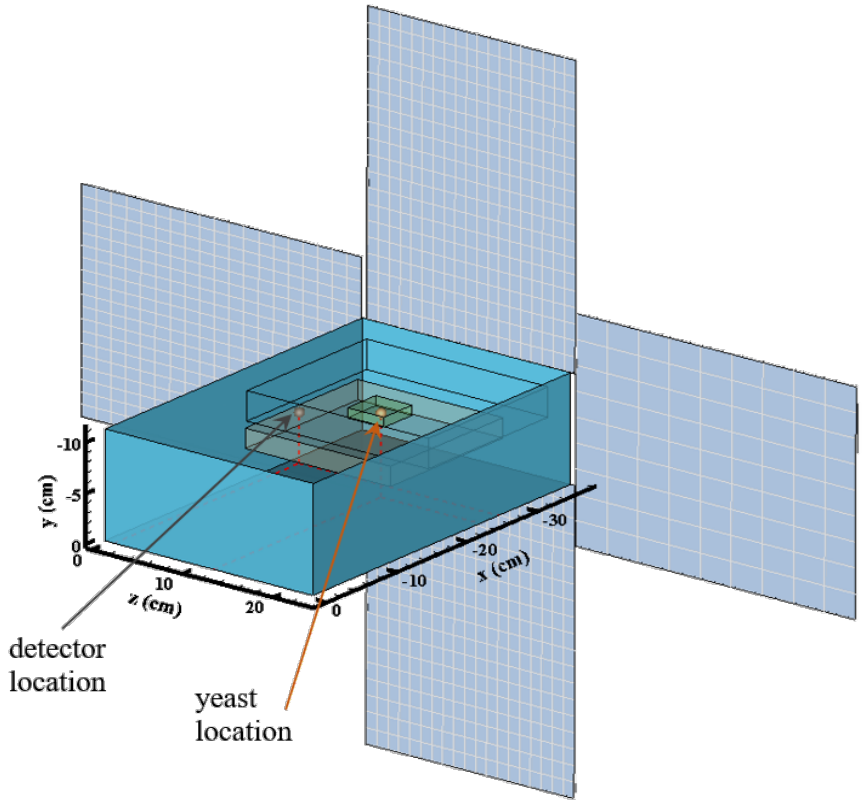
Component	Mass (kg)	Dimensions (cm)			Density (g/cm^3)	Material composition
		x-axis	y-axis	z-axis		
BioSentinel box	10.7	36.5	11.0	22.9	1.40	55% aluminum 30% polycarbonate 10% silicon; 5% FEP
Solar panel deployed	0.28 (each)	30.8	0.17	22.9	2.40	95% silicon 5% aluminum
Fluidic card (growth stage)	0.07	4.1	1.3	3.9	1.40	84.5% polycarbonate 10% stainless steel 5% copper; 0.5% water
Card box	1.4	20.0	3.0	16.5	1.40	54.7% polycarbonate 30% aluminum 10% stainless steel 5% copper; 0.3% water
Fluid bag box	0.76	16.5	2.0	16.5	1.40	40% FEP 24% polycarbonate 26% water 10% aluminum

BioSentinel Target Points in HZETRN

- Transport performed in 3D execution mode
- Dose, flux, and LET spectra are calculated at single target points within the BioSentinel geometry
  - Requires position and material assignment
- Two target points were defined to obtain response
  - Dosimeter location
  - Yeast location (Biological compartment)

Table 2: Target points for HZETRN2020 transport and response calculations.

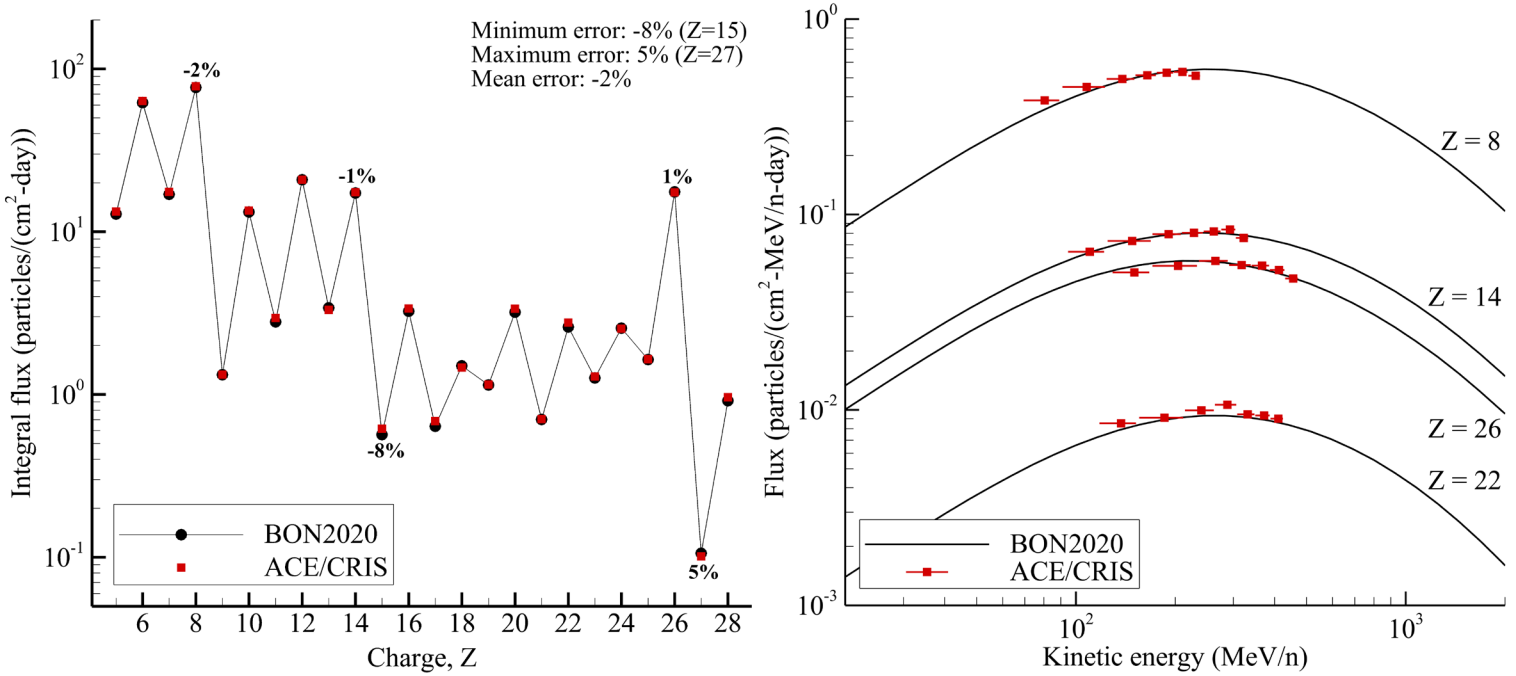
Target point	Target point location (cm)			Density (g/cm^3)	Material composition
	x	Y	z		
Detector	-26.3	-5.0	1.0	2.33	100% silicon
Yeast dry stage	-23.7	-8.3	12.0	1.22	~100% Trehalose ~0.05% cells (omitted)
Yeast growth stage	-23.7	-8.3	12.0	1.009	97.3% water 0.65% Nitrogen base 1.95% Dextrose 0.1% Trehalose <0.001% cells (omitted)



[Rahmanian et al. (2023)]

Modelling Ambient GCR Environment

- Badhwar-O'Neill 2020 (BON2020) GCR model was used in HZETRN
- BON2020 agrees well with ACE/CRIS measurements for the BioSentinel mission



[Rahmanian, Slaba, George, Braby, Bhattacharya, Straume and Santa Maria. (2024)]

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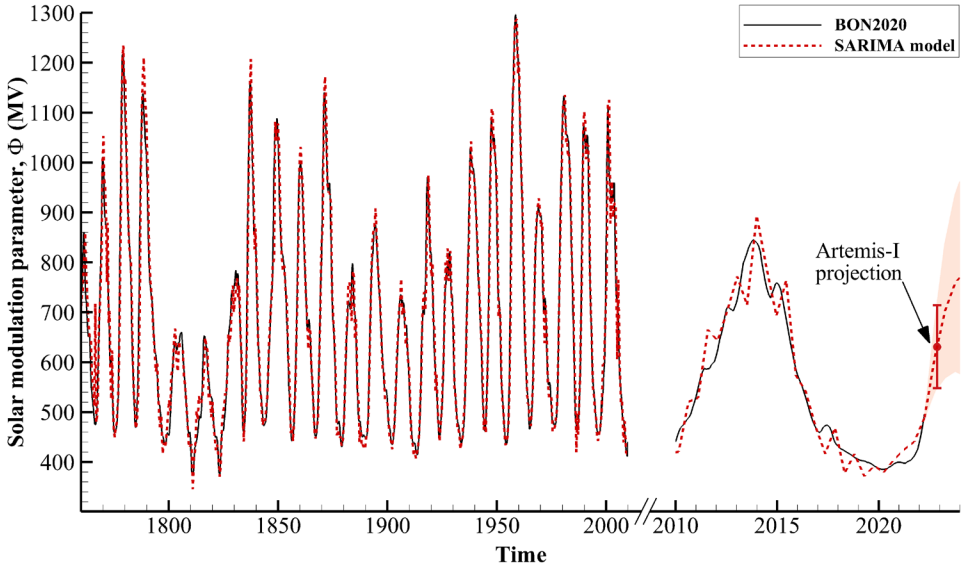
Solar Cycle Prediction for the GCR

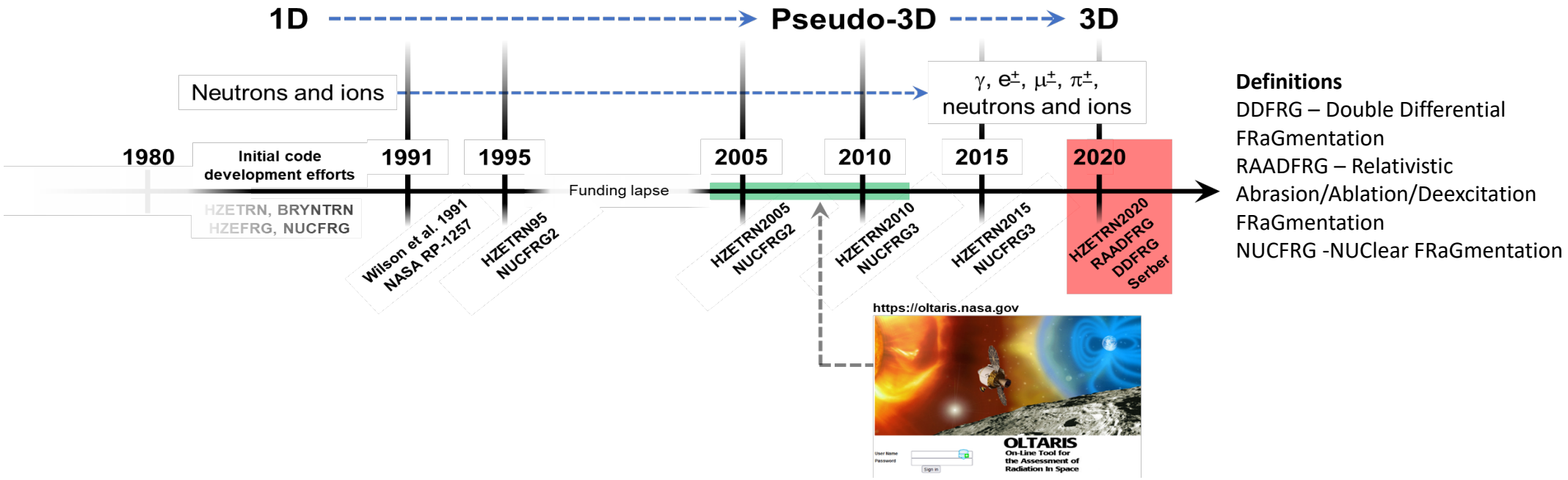
- An important component of BON2020 GCR model, is a parameter related to the solar cycle: Solar modulation parameter ϕ
- The initial BioSentinel model predictions were calculated prior to the mission
  - Required to predict solar modulation parameter
  - Used forward forecasting tool



[Rahmanian et al. 2023]

Physics Models for HZETRN

- Nuclear physics model describes pion, nucleon, and light ion production
  - Specific models have been developed for HZETRN appropriate for space applications
  - Combined models cover the particles and energies relevant for space radiation

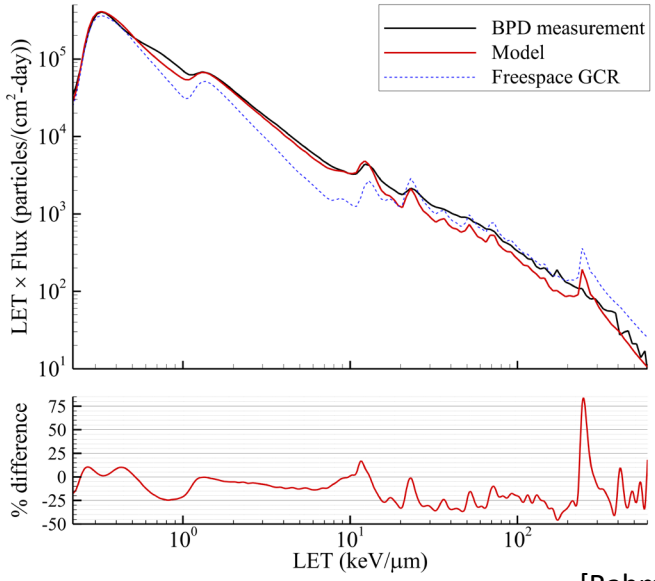


Definitions
DDFRG – Double Differential FRaGmentation
RAADFRG – Relativistic Abrasion/Ablation/Deexcitation FRaGmentation
NUCFRG -NUClear FRaGmentation

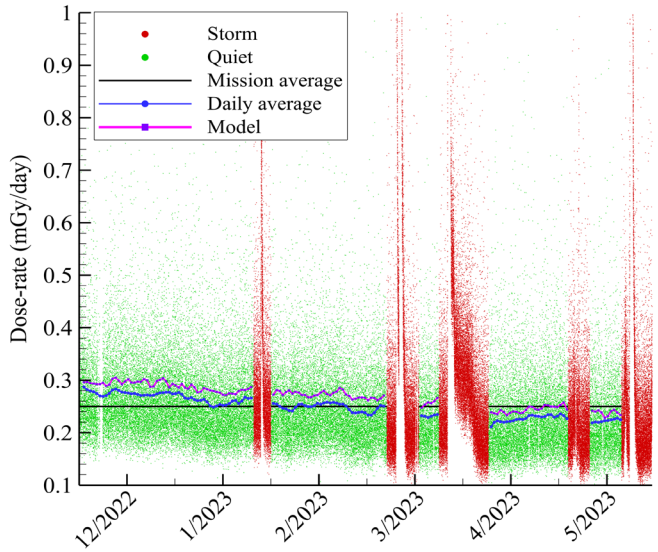
[Image Courtesy of Tony Slaba]

Comparison of Model Predictions and BioSentinel Spaceflight Measurement

- Good agreement between GCR model predictions and measurements for both average dose rate and LET spectrum (particularly below 10 KeV/um)



	Dose-rate (mGy/day)
BPD measurement	0.250
Model Post Mission Calculation	0.264 (6%)
Model Pre-Mission Prediction	0.27 ± 0.04 (8%± 16%)



[Rahmanian, Slaba, George, Braby, Bhattacharya, Straume and Santa Maria. (2024)]

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Summary

- The BioSentinel mission provided an opportunity to compare modelling results obtained from NASA's deterministic transport code (HZETRN) and spaceflight measurements.
- Model prediction showed good agreement with measurement data.
- For spaceflight experiments, modelling with transport codes can provide a great tool to predict dose and LET spectrum for targets of interest (detector and biological compartment) and guide experimental design.